FIELD OPTIMIZED 4-ROD RFQ MODEL*

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Abstract

The performance of an RFQ in case of its beam quality and transmission is in the basis dependent on the conformity of the field distribution of the manufactured structure with the one of its particle dynamic design. In the last years studies have been performed on the influence of various elements of the 4-rod RFQ on its field distribution. In particular the tuning process of the 4-rod RFQ with its tuning plates has been optimized. These studies have been complemented with detailed simulations on the fringe fields at the end of the electrodes and the conformity of the fields along the structure as well as the influence of other tuning elements like the piston tuner. Based on the findings of this research a proposal for a field optimized 4-rod RFQ model has been developed and will be presented in this paper.

INFLUENCE OF THE FIELD DISTRIBUTIONS ON THE PARTICLE BEAM

The 4-rod Radio Frequency Quadrupole (RFQ) is operated in its "π-0-mode". This means that the electric field is constant along the structure, resonating in a 0-mode, while the orientation of the magnetic field changes from RF cell to RF cell in a π-mode. The corresponding normal electric field on the electrodes and the surface currents on the structure are shown in Fig. 1 together with the transverse and longitudinal electric field distribution of this mode.

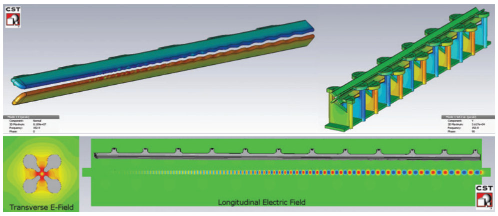

Figure 1: The operation "π-0" mode of the 4-rod RFQ.

The main characteristic of RFQs is the simultaneous focusing, bunching and acceleration of an ion beam with the RF quadrupole field. The field distribution that is required for a certain application is fixed in the particle dynamic design. Deviations from this design distribution can have a strong influence on beam parameters like for example the output energy or the transmission efficiency, or power requirement, of the RFQ. This effect can be split in the influence of the transverse and longitudinal electric field.

Longitudinal Fields

The longitudinal field distribution between the electrodes is fully defined by their modulation profile. But the boundary fields of the quadrupole can have a similar effect like an acceleration gap between two drift tubes. Their influence depends strongly on the phase when the particles leave the quadrupole, corresponding to the transit time factor. The field amplitude is at 50% of its maximum on the falling edge of the RF in the classical case, where the modulation ends with a full acceleration cell. But with a transition cell (see [1]) at the end the synchronous particle enters the gap at 90% of the full amplitude of the electric field on its rising edge. The geometric situation at the end of an RFQ is shown in Fig. 2.

Figure 2: View of the geometrical situation at the end of the 4-rod electrodes.

This effects have been studied for example of the FNAL H^--Injector in [2]. For this RFQ changes in the output energy in the order of a view percent have been observed [2] [3]. Detailed discussions about the origin of these boundary fields are given in [4] and [5].

Transverse Fields

The focusing strength B is defined by

$$B = \chi \frac{qe\lambda^2}{mc^2} \frac{V}{a^2}$$

with the geometric parameter χ, the ion charge to mass ratio q/m, the elementary electric charge e, the speed of light c, the electrode voltage V and the aperture a. So the transverse field distribution dominates the transmission characteristic and bunching efficiency of the RFQ. Figure 3 shows the results of simulations with a reduced electrode voltage (respectively focusing strength) in comparison with the original design of the FNAL RFQ [4]. While the original design has a transmission of 99.67%, the case of the reduced focusing strength in the bunching section of the RFQ shows a transmission of less than 60%.

This effect can be compensated by a higher average electrode voltage what can lead to enhanced power requirements of the RFQ in the order of 20–30%. Additional simulations show that similar deviations at the beginning and end of the RFQ have a much smaller influence on the transmission [2].

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* Work supported by BMBF

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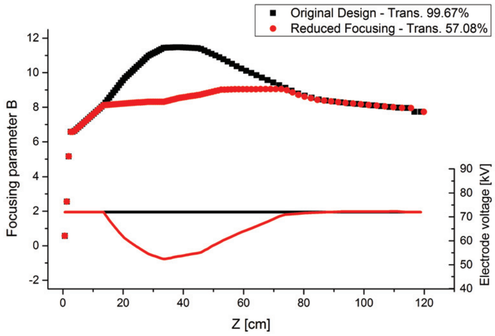

Figure 3: Simulation of the RFQ's transmission with the design voltage and reduced voltage in the bunching section.

SIMULATIONS ON THE FIELD DISTRIBUTION

In [2], [5] and [3] the influence and origin of the 4-rod electrode's boundary fields have been studied. Based on this further investigations on the symmetries in the 4-rod RFQ and its potential distribution have been performed in [4].

Figure 4 shows a simulation of the current distribution on a 4-rod structure. It is clearly visible that the current on the outer side of the last stem is reduced compared to the inner stems. For the quantification of this phenomenon the "stem voltage" U_{Stem} was introduced. It corresponds to the voltage on an integration path from the side of an stem arm to the vessel wall.

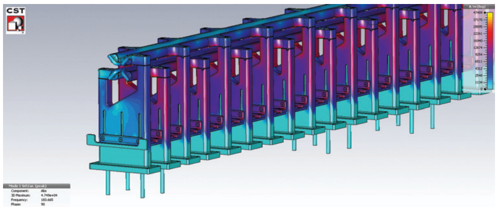

Figure 4: Current distribution on the 4-rod resonator.

U_{Stem} is plotted along the length of an RFQ of each of its electrodes in Fig. 5. This picture includes three main points of information. (i) There is a potential distribution along one electrode that reminds of the oscillation from a fixed to an open end. The amplitude is maximal at the open end while the other one nearly shows a short cut behavior. The last stem with the fixed electrode pair has about 15% of U_{Stem} at the second last stem where the free electrode pair is connected. Two neighboring stems in the middle of the RFQ show a difference in U_{Stem} by 2%. (ii) The difference in U_{Stem} comparing the upper or lower two electrodes reflects the shape of the field flatness deviation. (iii) The difference in U_{Stem} for one electrode pair, for example X (top) and X (low), shows a dipole effect in the quadrupole symmetry like it is studied in [6].

Using this voltage U_{Stem}, the influence of the electrodes overlap on the potential distribution is studied in Fig. 6. The overlap is the part of the electrodes that reach over the last stem. Each electrode pair is connected to every second stem, so one pair is fixed on the first stem and free on the last stem and the other way around for the other pair. In the simulation shown in Fig. 6 the stem voltage for one electrode that is fixed on the last stem, is compared at the last and a middle stem for a growing overlap. U_{Stem} for the middle stem is about double the value than at the last stem. This ratio stays nearly the same on the whole simulation range for the length of the overlap. Going to even longer overlaps will cause mechanical instabilities, so this parameter can not be used to balance the potential distribution on the stems.

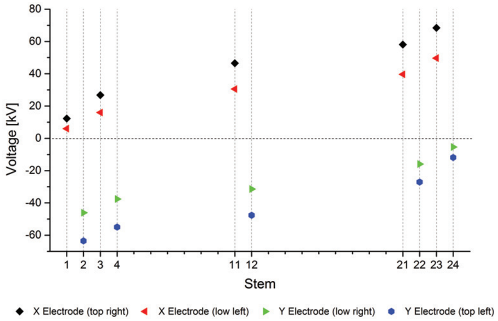

Figure 5: Layout of papers.

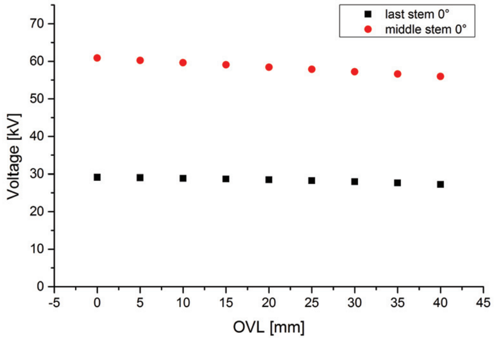

Figure 6: The stem voltage for one electrode at a fixed end a in the middle of the RFQ with growing overlap.

In order to balance the asymmetries of the electrodes potential at their ends, several modifications of the end stem geometry in the 4-rod structure have been tested. Three cases are shown in Fig. 7. In the first and third of them, the design of the last stem is modified to raise the magnetic field around the stem. The two attempts are either by enlarging the arms of the stem so that the stem is reduced to consist of two columns, or by giving the stem a waist shape. The second case shows extra elements that are connected in the face of the electrodes at the vessel wall to build an extra capacitance, drawing potential on the end of these electrodes.

The results of this study are presented in Table 1. In comparison to a standard 4-rod design (as shown on Fig. 2) U_{Stem} for the last stem could be raised by about 5% in the cases "Column" and "Waist", while the extra capacitance does not affect the electrode potential.

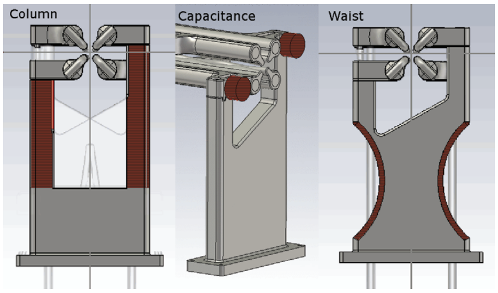

Figure 7: Variations of the end geometry.

Table 1: Comparison of U_{Stem} of the Last Stem with the Second Last and Middle Stem

Case	U_{Stem}	
	Last/Second	Last/Middle
Standard Design	17%	24%
Column	21%	29%
Capacitance	17%	24%
Waist	22%	31%

POSSIBILITIES FOR THE FIELD OPTIMIZATION

In [5] possibilities to influence the boundary field by changes in the overlap geometry with respect to the dimension of the last RF cell and the vessel wall have been developed. Next to that the optimization of the longitudinal field flatness with reduced length of the outer RF cells has been proposed [6]. First attempts on that are also shown in [7].

Based on these studies and the simulations presented in this paper a proposal for an optimized field distribution in the 4-rod RFQ has been developed. The three main points of this model are (i) a reduced stem distance in the last RF cells, (ii) enhanced space for the magnetic field around the last stem and (iii) positioning of the RF shielding. They are marked in Fig. 8.

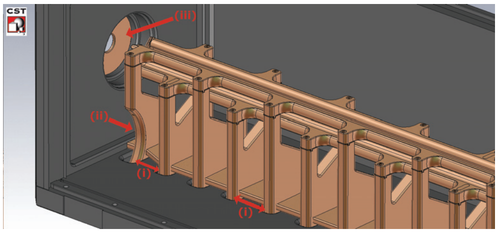

Figure 8: Proposal for a field optimized 4-rod RFQ model with (i) reduced length of the last RF cells, (ii) enhanced space for the magnetic field around the last stem and (iii) optimized position of the RF shielding.

By reducing the stem distance in the last RF cells the transverse field distribution can be regulated already in the design of the RFQ. In addition it allows to shift the tuning elements into the RFQ to optimized positions. As it was shown in [5] this reduces also the boundary fields of the electrodes, so that there is a second benefit of the shorter end cells. Beside that, they produce an overlap in combination with bigger distance between vessel wall and last stem. In [5] it is shown that this setup of the last stem with the vessel wall and overlap can reduce the boundary fields by a factor of 1.44. Together with a waist design of the last stem this enhances the space for the magnetic field in the boundaries what helps to balance the potential distribution on the electrodes. The last point, the influence of the positioning of the RF shielding plate, was discussed in detail in [2]. It has a strong influence on the boundary fields of the electrodes, because they can reach into the opening in the RF shielding when it is attached to the inside of the vessel wall. In some cases its aperture needs to be opened to reduce the amplitude of the boundary fields. By transferring the shielding plate to be fixed at the outside of the vessel, its influence is reduced considerably. A detailed analysis of all these points can be found in [4].

Each of this modifications has only a small influence on the field distributions in the 4-rod RFQ. But with the combination of all of them, the field symmetry of the 4-rod structure can be enhanced and an optimized performance of the RFQ can be achieved.

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